A proof of concept for MR-only workflow in CyberKnife intracranial radiosurgery

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Purpose/Objective:
CyberKnife® (Accuray Inc.) radiosurgery relies on CT images for precise dose calculations and generating digital reconstructed radiographs (DRRs) for kV x-ray based image-guided treatment delivery. To enhance the accuracy of target and organ at risk delineation, MR images are routinely acquired and co-registered with the treatment planning CT scan. However, this procedure introduces a registration uncertainty, which is propagated throughout the treatment. Implementing an MR-only workflow using synthetic CTs eliminates registration uncertainties, while optimizes patient comfort and the imaging resources necessitated for treatment planning. In this study, we implemented an MR only workflow for intracranial CyberKnife radiosurgery, utilizing artificial intelligence (AI) techniques to generate synthetic-CT (sCT) images from MRI scans. These sCTs were used for dose calculations and DRR generation.

Material/Methods:
A complete set of planning CT along with co-registered T1w-MR images, DRRs and treatment plan details for ten acoustic neurinoma cases equally distributed to both sides of skull base, were exported from the CyberKnife database. SCTs were generated using a novel AI based model. This model was trained using an end-to-end ensemble approach, integrating self-supervised Generative Adversarial Networks (GANs) with focus on cycle consistency, leveraging both planning CTs and T1w-MRIs of the brain as references. The training dataset comprised a retrospective cohort featuring pairs of CT and co-registered MR images obtained from different hardware vendors. sCTs of 1 mm slice thickness, 512 x 512 reconstruction matrix and a 25.5 cm field of view (FOV) were generated from the co registered patient T1w-MR scans and imported into the CyberKnife system for DRR generation. The sCT-based DRRs (sDDRs) were then exported and compared with the corresponding CT-based DRRs using the structure similarity index (SSIM) and Dice coefficient. Dosimetry was performed using a ray-tracing based dose calculation algorithm developed in-house that accounts for tissue heterogeneities using the effective path length of each voxel traced by the beam. For each case two dosimetry calculations were performed, using either the CT or the sCT, but the same treatment planning parameters (i.e., beam position and orientation, Monitor Unit per beam, etc). Dose results for each case were compared with respect to target coverage, the maximum brainstem dose and the mean dose to the ipsilateral cochlea.

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Results:

The sCTs and sDRRs displayed similar visualizations compared to their corresponding CT and DRR counterparts, although exhibiting decreased contrast (see Figure 1). The mean Dice coefficient and SSIM index between the DRRs and sDDRs were 0.96 ± 0.1% and 0.91 ± 0.4%, respectively. The mean difference in the target volume covered with the prescribed isodose surface was found equal to 4.3% ± 4.8%. Moreover, the mean difference in the maximum dose to the brainstem and mean dose to the ipsilateral cochlea were found equal to 3.4% ± 8.7% and 4.3% ± 4.8%, respectively. The observed differences could be attributed to the absence of imaging data in the oral cavity in the MRI images, and therefore in the sCTs, that is included in the CTs and DRRs, as well as to the reduced contrast of the sCTs affecting the effective path length calculations.

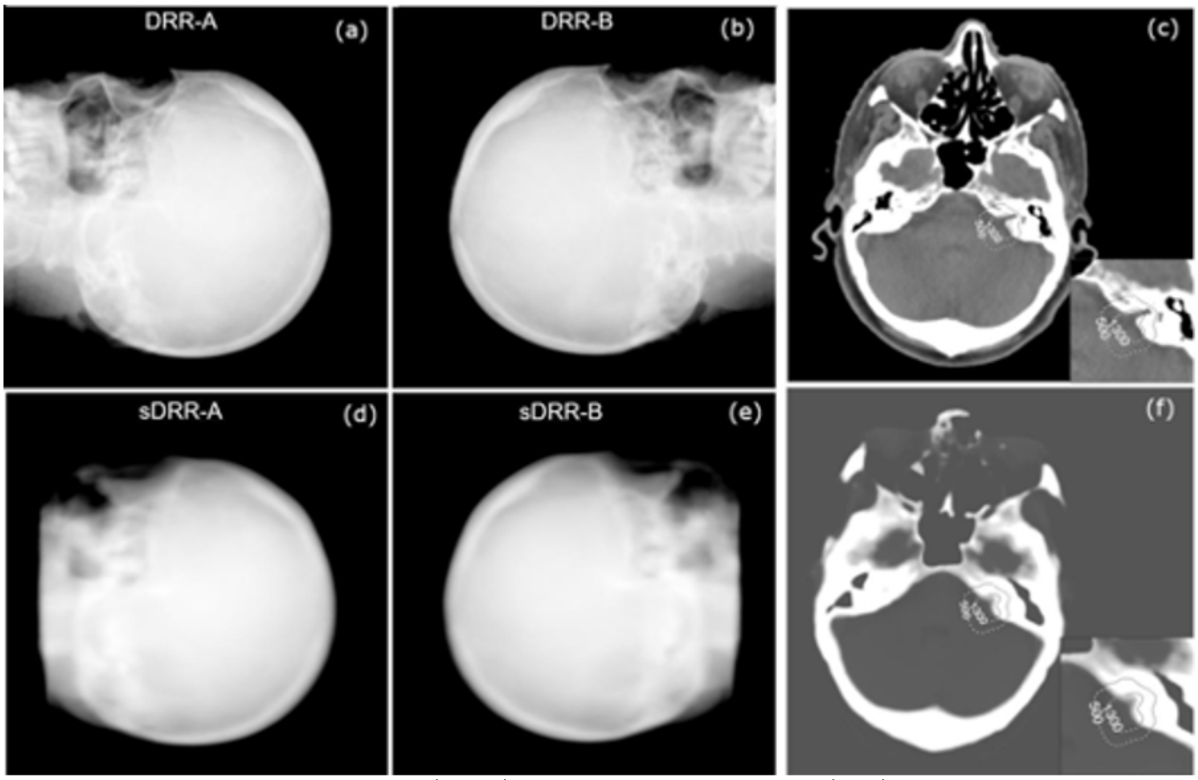

Figure 1. Digital reconstructed radiographs (DRRs) for the two projections (A, B) of the CyberKnife image guide system calculated using the CT (a, b) and the synthetic CT (d, e) for an indicative case. Axial CT (c) and sCT (f} slices depicting the dose distributions calculated using the CT (solid lines) and sCT (broken line) are also shown..

Conclusion:

In this study, we have provided a compelling proof of concept that an AI-based approach to generate synthetic CTs offers a viable solution for an effective implementation in CyberKnife intracranial radiosurgery. AI based sCTs obviate the need for manual structure segmentation or acquisition of special MR sequences. However, prior to its clinical adoption, it is imperative that the MRI scanning protocol encompasses the entirety of the head & neck region, and further refinements should be made to the AI model to augment the contrast of the generated sCTs, thereby optimizing their utility in this critical medical application.